Observations of Type Ia Supernovae, and Challenges for Cosmology

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Summary. Observations of Type Ia supernovae (SNe Ia) reveal correlations between their luminosities and light-curve shapes, and between their spectral sequence and photometric sequence. Assuming SNe Ia do not evolve at different redshifts, the Hubble diagram of SNe Ia may indicate an accelerating Universe, the signature of a cosmological constant or other forms of dark energy. Several studies raise concerns about the evolution of SNe Ia (e.g., the peculiarity rate, the risetime, and the color of SNe Ia at different redshifts), but all these studies suffer from the difficulties of obtaining high-quality spectroscopy and photometry for SNe Ia at high redshifts. There are also some troubling cases of SNe Ia that provide counterexamples to the observed correlations, suggesting that a secondary parameter is necessary to describe the whole SN Ia family. Understanding SNe Ia both observationally and theoretically will be the key to boosting confidence in the SN Ia cosmological results.

1 Observations of SNe Ia and the Accelerating Universe

Spectroscopic observations of nearby Type Ia supernovae (SNe Ia) reveal that they can be divided into several subclasses: the majority are the so-called "normal" or "Branch normal" SNe Ia (Branch, Fisher, & Nugent 1993), while the others are "peculiar" SNe Ia which can be further divided into SN 1991T-like or SN 1991bg-like objects (see Filippenko 1997, and references therein). Li et al. (2001a) discuss SN 1999aa-like objects as another potential subclass of the peculiar SNe Ia. The classification is based on the spectra of SNe Ia before or near maximum light: normal SNe Ia show conspicuous features of Si II, Ca II, and other intermediate-mass elements (IMEs; e.g., S II, O I); SN 1991T-like objects show unusually weak IME lines, yet prominent high-excitation features of Fe III; SN 1991bg-like objects have strong IME features, plus a broad Ti II absorption trough around 4100 Å and enhanced Si II/Ti II $\lambda5800$ absorptions. SN 1999aa-like objects are similar to the SN 1991T-like ones, but with significant Ca II H & K absorption lines.

Photometric observations of nearby SNe Ia also reveal a correlation between the peak luminosity and light-curve shape (LLCS correlation, here-

after). This was first convincingly demonstrated by Phillips (1993), and subsequently exploited by Hamuy et al. (1996a), Riess, Press, & Kirshner (1996), Perlmutter et al. (1997), and Phillips et al. (1999). The slower, broader light curves are intrinsically brighter at peak than the faster, narrower light curves. Various parameters have been proposed to quantify the "speed" of the light curve, such as $\Delta m_{15}(B)$ (the decline in magnitudes between peak brightness and 15 days later in the B band), Δ (the difference in magnitudes between the peak brightness of a SN Ia and a nominal standard SN Ia), s ("stretch factor," the amount of stretch applied to the light curve (generally B band) of a SN Ia to match those of a nominal standard SN Ia), and various empirical methods have been developed to calibrate the peak absolute magnitudes of SNe Ia (Phillips 1993; Hamuy et al. 1996a; Riess, Press, & Kirshner 1996; Perlmutter et al. 1997; Jha 2002; Wang et al. 2003). The multi-color light-curve shape (MLCS) method, for example, has demonstrated the ability to achieve a scatter in the calibrated absolute magnitudes of SNe Ia to ~ 0.15 mag (Riess, Press, & Kirshner 1996).

By assuming that the observed correlation for nearby SNe Ia also applies to the objects at high redshift, utilizing the empirical calibration methods developed from nearby SNe Ia, and studying the Hubble diagram for SNe Ia at both low and high redshifts, the High-z SN Search Team (Schmidt et al. 1998) and the SN Cosmology Project (Perlmutter et al. 1997) have measured that high-redshift SNe Ia are fainter than expected, and interpreted this result as evidence that the expansion of the Universe is accelerating, due perhaps to a non-zero cosmological constant or some other forms of dark energy (e.g., Riess et al. 1998; Perlmutter et al. 1999; Tonry et al. 2003; Knop et al. 2003).

2 Challenges of the Accelerating Universe

The observational fact is that the SNe Ia at $z \approx 0.5$ are ~ 0.28 mag dimmer ($\sim 14\%$ farther) than expected in a Universe with $\Omega_M = 0.3$ and no cosmological constant. Besides the interpretation of a positive cosmological constant, other possible alternatives have been proposed as follows.

1. Luminosity evolution. Two important questions are (a) whether the high-redshift SNe Ia follow the same LLCS correlation for the nearby objects, and (b) whether the SNe Ia at $z \approx 0.5$ are intrinsically fainter than nearby SNe Ia by 0.28 mag after correction for the LLCS correlation.
2. Interstellar dust, which produces more extinction of the high-redshift SNe Ia and makes them look apparently fainter.
3. Selection bias: preferentially fainter SNe Ia are observed at high redshift.
4. Gravitational lensing: the inhomogeneous distribution of matter in the Universe deamplifies the observed brightness of most high-redshift SNe Ia.

Among these, ordinary dust is not considered a viable option, as it introduces too much reddening in the colors of SNe Ia at high redshift (Riess et

al. 2000) and more dispersion in the distance measurements than is currently observed. "Grey" dust (Aguirre 1999a,b), which leaves little or no imprint on the spectral energy distribution of a SN Ia, could be more pernicious, but the amount of grey dust required to explain the faintness of high-redshift SNe Ia would also distort the cosmic microwave background, an effect which has not been seen. Moreover, it still introduces more distance dispersion than is currently observed. Tonry et al. (2003) also provided evidence that a systematic effect which goes as a power law of $(1 + z)$, such as extinction by dust, is not likely to match the SN Ia data. No known selection bias favors detection of intrinsically fainter SNe Ia at high redshift. Malmquist bias may afflict the nearby SN Ia sample so preferentially brighter objects were observed, but the effect is shown to be small (Riess et al. 1998; Perlmutter et al. 1999). Moreover, the high-redshift SN Ia sample should be subject to the same bias to a greater extent, since most high-redshift SN searches are magnitude-limited. Gravitational lensing deamplification (Metcalf 1999; Barber 2000), typically $\sim 2\%$ at $z = 0.5$, is much smaller than the cosmological effect.

Luminosity evolution is arguably the most serious challenge to the cosmological interpretation of high-redshift SNe Ia. The cause of this is somewhat embarrassing: despite being the most luminous type of SN, SNe Ia have not been completely understood theoretically (see Leibundgut 2001 for a review), or have the progenitor system conclusively identified (see Livio 2000 for a review). Consequently, theory cannot provide conclusive guidance on whether or how SNe Ia and their progenitor systems evolve at different redshifts. Nevertheless, theorists have provided some insights into this question by studying the effects of metallicity and the C/O ratio of a white dwarf (WD), the agreed precursor to a SN Ia (e.g., von Hippel, Bothun, & Schommer 1997; Höflich, Wheeler, & Thielemann 1998; Umeda et al. 1999; Nomoto et al. 2003). Höflich, Wheeler, & Thielemann (1998) suggested that the effect of changing metallicity on the rest-frame visual and blue light curves is small, and as the C/O ratio of a WD becomes progressively lower at higher redshift, the luminosity of the resulting SN Ia becomes brighter for the same light-curve shape, an effect that is contrary to the cosmological result from SNe Ia. Umeda et al. (1999) and Nomoto et al. (2003) use the variation in the C/O ratio in the WD to explain the distribution of SN Ia brightness, but suggest that the diversity can be normalized by applying the LLCS correlation.

Answers to the question of whether SNe Ia evolve have also been sought from observations of them at different redshifts. The nearby sample is an excellent laboratory for studying possible luminosity evolution, since SNe Ia have been observed in a wide range of host-galaxy morphologies including ellipticals, spirals, irregulars, and dwarf galaxies. In fact, the range of metallicity, stellar age, and interstellar environments probed by the nearby SN Ia sample is much greater than the mean evolution in these properties for individual galaxies between $z = 0$ and $z = 0.5$. Some variation of the observed characteristics of SNe Ia has been noticed; for example, luminous events occur preferentially in metal-poor environments (Hamuy et al. 2000), and the lumi-

nosity of SNe Ia correlates with the projected distance from the host nucleus (Wang, Höflich, & Wheeler 1997). However, after correction for the LLCS correlation and extinction, the observed residuals from the Hubble flow do not correlate with host-galaxy morphology or the projected radial distances (Riess 2000; Sullivan et al. 2003). This suggests that the LLCS correlation applies to a wide range of stellar environments and is a strong argument against significant evolution to $z = 0.5$ (Schmidt et al. 1998).

The empirical test of luminosity evolution at high redshift has been focused on getting high-quality spectra and light curves, and comparing them with those of nearby SNe Ia. The assumption of this test is that significant luminosity evolution would be accompanied by other visibly altered observables of the SNe. Comparison of high-quality spectra between nearby and high-redshift SN Ia have revealed remarkable similarity (Riess et al. 1998; Perlmutter et al. 1999; Coil et al. 2000; Tonry et al. 2003). Riess et al. (2000) also obtained the rest-frame I-band light curve of the high-redshift SN Ia 1999Q, which displayed the secondary maximum that is typical of normal nearby SNe Ia.

To date, there is no clear, direct evidence that suggests significant luminosity evolution for SNe Ia at different redshift. To rest the case of luminosity evolution, however, we need to fully understand the models of SNe Ia and how they evolve at different redshifts. Without a firm theoretical footing, we must conservatively demand that **all** observables of high-redshift SNe Ia be statistically consistent with their nearby counterparts.

In the following sections, we discuss in more detail some of the recent comparisons done on the observables and characteristics of SNe Ia at different redshifts, which mag suggest possible differences between high-redshift SNe Ia and their nearby counterparts.

2.1 Peculiarity Rate at Different Redshifts

The rate of "peculiar SNe Ia" in the nearby sample has been recently measured by Li et al. (2001a). They used a **distance-limited** sample of SNe Ia from the Lick Observatory Supernova Search (LOSS; Filippenko et al. 2001) and performed Monte Carlo simulations (Li, Filippenko, & Riess 2001) demonstrating that essentially all SNe Ia should have been discovered in the sample galaxies of LOSS. Within this unbiased sample they found a rate of $\sim$20% for the SN 1991T/1999aa-like objects and $\sim$16% for the SN 1991bg-like objects, for a total peculiarity rate of $\sim$36%.

However, in the now more than 100 spectroscopically classified SNe Ia at high redshift, there has not been a single unambiguously peculiar SN Ia reported. While the lack of SN 1991bg-like objects could be explained by their intrinsic faintness and low expected rate in **magnitude-limited** searches, the lack of SN 1991T/1999aa-like objects is puzzling.

Li et al. (2001a) offered several possible explanations for the difference between the peculiarity rate of SNe Ia at different redshifts: extinction toward the SN 1991T/1999aa-like objects, difficulty in identifying peculiarities

in poor-quality spectra of the high-redshift SNe Ia, and most importantly, the "age bias": the peculiarity of SN 1991T/1999aa-like objects can only be easily identified in early-time spectra. This same bias may also explain why the Calán/Tololo survey, a nearby magnitude-limited SN search, yielded no SN 1991T/1999aa-like objects among 29 SNe Ia (Hamuy et al. 1996b).

If, however, these observational biases are not to blame, the absence of peculiar SNe Ia at high redshift could result from an evolution of the population of progenitor systems: certain progenitor channels at high redshift may be lost due to a redshift-dependent variation in the mass, composition, and metallicity of SN Ia progenitors (e.g., Ruiz-Lapuente & Canal 1998; Livio 2000). It is thus an important challenge to observationally identify some peculiar SNe Ia at high redshifts, to definitively rule out luminosity evolution as the cause of the difference in the peculiarity rate of SNe Ia at different redshifts.

2.2 Risetime at Different Redshifts

The risetime is defined as the time interval between the explosion and the maximum brightness of a SN Ia. Precise knowledge of the SN Ia risetime, which is sensitive to the ejecta opacity and the distribution of ^{56}Ni, provides constraints on models of SN Ia progenitors. A comparison of the risetime for high-redshift and nearby SNe Ia is thus a valuable test of luminosity evolution.

The risetime for the nearby SNe Ia was measured by Riess et al. (1999). They collected about 25 measurements of SNe Ia between 10 and 18 days before B maximum, normalized them to a fiducial risetime curve, and measured a risetime of 19.98 ± 0.15 days. A preliminary risetime for the high-redshift SNe Ia was measured by Goldhaber (1998) from the Supernova Cosmological Project (SCP) data as 17.50 ± 0.40 days, which is discrepant from the nearby risetime at a statistical likelihood greater than 99.99% (5.8σ). Aldering, Knop, & Nugent (2000), however, refined the risetime for the high-redshift SNe Ia in the SCP data to 17.50 ± 1.20 days, a $\sim 2\sigma$ difference from the nearby measurement. They also suggested that under extreme situations the risetime could be biased up to 2–3 days due to observational biases and fitting methods.

It remains to be seen whether the risetimes of high-redshift and nearby SNe Ia are statistically inconsistent when a better risetime measurement is derived for the high-redshift SNe Ia. It should also be noted that even if the two risetimes are inconsistent with each other, it is unclear whether the difference in risetime could be translated into a difference in peak luminosity: most current theoretical models have difficulties in reproducing the observed risetimes and the correlation between risetime and peak luminosity.

2.3 Intrinsic Color at Different Redshifts

To date, there is no consensus on the precise intrinsic colors of SNe Ia with different photometric behaviors. As a result, there is not a good theoretical or empirical method to accurately determine host-galaxy extinction to SNe Ia,

and observers often have to resort to priors such as applying the Galactic reddening law to the host galaxies of SNe Ia, and assuming all SNe Ia have the same intrinsic color at maximum. Phillips et al. (1999) proposed a method to estimate the host-galaxy reddening to a SN Ia by using its color at 30–60 days past maximum, but Li et al. (2001b) showed that this method does not apply to all objects. The extinction correction is a major source of uncertainty in the current empirical fitting methods. To circumvent this difficulty, people often use subsamples that are likely to have low extinction at both low and high redshifts. Fortunately, Hatano, Branch, & Deaton (1998) showed that most SNe Ia should have low extinction.

Different methods for treating the extinction correction in the fitting process yield different results in the intrinsic color comparison of SNe Ia at a range of redshifts. Leibundgut (2001) and Falco et al. (1999) suggested that there is evidence from the $E(B-V)$ values in Riess et al. (1998) that high-redshift SNe Ia are statistically bluer than their nearby counterparts, but analysis by Perlmutter et al. (1999) showed no such effect, nor did a recent compilation of 11 high-redshift SNe Ia observed by the *Hubble Space Telescope* (Knop et al. 2003). The problem of extinction correction will continue to plague the empirical fitting methods until a better understanding of the intrinsic colors of SNe Ia is achieved, and the influence of extinction corrections on the cosmological conclusions needs to be investigated in more detail. Drell, Loredo, & Wasserman (2000), for example, attributed the difference in colors to luminosity evolution, while Knop et al. (2003) suggested that reasonable changes in colors do not have a significant impact on the cosmological results.

2.4 Peculiar Nearby SNe Ia

A fundamental assumption of the current empirical fitting methods is that the light curves of all normal SNe Ia can be represented by a single parameter such as $\Delta m_{15}(B)$, Δ, or s. However, there is growing evidence that not all SNe Ia form a one-parameter family. Branch (1987) showed that normal SNe Ia could have very different expansion velocities. Hamuy et al. (1996c) showed that some light curves with similar decline rates have significant differences in particular details. Hatano et al. (2000) also demonstrated that the spectroscopic diversity among SNe Ia is multi-dimensional.

The SN 1991T-like and SN 1991bg-like objects, though categorized as peculiar SNe Ia, generally follow the LLCS correlation and the spectrum–luminosity sequence — i.e., they seem to be an extension of the one-parameter description of normal SNe Ia. Some more disturbing cases of peculiar nearby SNe Ia that fail the one-parameter description are SN 2000cx (Li et al. 2001; Candia et al. 2003), SN 2002cx (Li et al. 2003), SN 2001ay (Nugent et al. in preparation), and SN 2002ic (Hamuy et al. 2003).

The peculiarity of SN 2000cx is that its light curves cannot be fit well by the existing fitting methods. There is an apparent asymmetry in the B-band peak, in which the premaximum brightening is relatively fast (similar to that

of the normal SN 1994D), but the postmaximum decline is relatively slow (similar to that of the overluminous SN 1991T). SN 2000cx has very blue colors and also unique spectral evolution. Its premaximum spectra are similar to those of SN 1991T-like objects, but the high-excitation Fe III lines remain prominent until well after maximum. The expansion velocities derived from the absorption features are unusually high and evolve differently than normal. Though it has a slow light curve, its estimated luminosity is average (Li et al. 2001) or even slightly subluminous (Candia et al. 2003).

SN 2002cx has many properties that are the opposite of those of SN 2000cx. It has a premaximum spectrum similar to that of SN 1991T, a decline rate in the B-band similar to that of normal SNe Ia, but a luminosity similar to that of the very subluminous SN 1991bg. It has a very red color evolution, and has extremely low expansion velocities measured from spectral features. The R and I-band light curves have a peculiar plateau phase around maximum. The late-time decline rate in all $BVRI$ bands is unusually slow. SN 2003gq (Filippenko & Foley 2003) may be another event that is similar to SN 2002cx.

SN 2001ay has a normal near-maximum spectrum, except that it has very high expansion velocities. The light curves of SN 2001ay are the slowest ever recorded, yet it has a normal luminosity. It also has a peculiar red color evolution until 30 days after maximum.

SN 2002ic is the only SN Ia to have shown direct evidence of SN ejecta interacting with the circumstellar medium (CSM). Its near-maximum spectrum is similar to that of SN 1991T, but diluted in strength. There are remarkable Balmer lines in later spectra, with $H\alpha$ showing an unresolved component (FWHM < 300 km s^{-1}) superimposed on a broad resolved base (FWHM $\approx$ 1800 km s^{-1}), similar to those observed in Type IIn SNe (Filippenko 1997). The spectral features and photometric behavior of SN 2002ic suggest that it has a very dense CSM. Based on these observations, Hamuy et al. (2003) ruled out the double-degenerate model for SN 2002ic, and suggested that the progenitor system involves a white dwarf and an asymptotic giant branch star. Livio & Riess (2003), however, argued that the opposite may be true: SN 2002ic results from a rare circumstance in which the SN Ia ejecta interact with the previously ejected common envelope of a double-degenerate system.

Although the frequency of these peculiar SNe Ia is low, and statistically they will not challenge the established empirical correlations, we need to understand why they are peculiar, and how they can be fit into the whole picture of SN Ia theories and observations. These objects with unusual properties might represent the general models of SNe Ia under extreme conditions, and studying them will provide clues to the theoretical models and progenitor systems. It is interesting to note that three of the four peculiar SNe Ia (SNe 2000cx, 2002cx, and 2001ay) all have very unusual expansion velocities, and three (SNe 2000cx, 2002cx, and 2002ic) show spectral features similar to those of SN 1991T. The subclass of SN 1991T/1999aa-like objects may thus be more heterogeneous than other SNe Ia, and objects with unusual expansion velocities should be treated with caution when used as cosmological tools.

3 Conclusions

Many alternatives have been proposed to explain the SN Ia data at different redshifts, but so far none has seriously challenged the accelerating Universe result. We have found no clear, direct evidence that SNe Ia at different redshifts evolve, though some studies show that there may exist some differences in their peculiarity rate, risetime, or colors.

The key to boosting confidence in the cosmological results from SNe Ia is to understand SNe Ia both theoretically and observationally. We need to theoretically identify the elusive progenitor systems for SNe Ia, and find out the cause of the diversity of SNe Ia. Similarly, we need to continue to search for SN/CSM interactions such as that observed in SN 2002ic, and place stringent constraints on the accretion history of SN Ia progenitors. We also need to re-examine existing observations of SNe IIn, to investigate whether SN 2002ic is an isolated case, or whether some additional SNe IIn are actually SNe Ia with strong SN/CSM interaction. For nearby SNe Ia, we need to develop better methods to measure host-galaxy extinction than currently available, study the environmental effects, find more empirical correlations, and develop a subclassification scheme that possibly links to different progenitor channels. We should continue to study those SNe Ia that are clearly discrepant. For high-redshift SNe Ia, we need to identify some peculiar SN 1991T-like or SN 1991bg-like objects, get better risetime measurements, obtain more high-quality spectra and light curves, and compare them with those of nearby SNe Ia. The ESSENCE project (e.g., Garnavich et al. 2002), SNAP satellite (http://snap.lbl.gov/), and the higher-z project (Riess 2002) are prime examples of current and future extensive studies of high-redshift SNe Ia.

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